

Long and Short GRB

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We report evidence from the 3B Catalogue that short ($T_{90} < 10$ s) and long ($T_{90} > 10$ s) GRB represent different populations and processes: Their spectral behavior is qualitatively different, with short bursts harder in the BATSE range, but chiefly long bursts detected at higher photon energies; $\langle V/V_{max} \rangle = 0.385 \pm 0.019$ for short GRB but $\langle V/V_{max} \rangle = 0.282 \pm 0.014$ for long GRB, differing by 0.103 ± 0.024 . Long GRB may be the consequence of accretion-induced collapse, but this mechanism fails for short GRB, for which we suggest colliding neutron stars.

INTRODUCTION

The durations of “classical” gamma-ray bursts (GRB) are bimodally distributed and are anti-correlated with their spectral hardness as measured by BATSE (1). Little attention has been paid to the cause of this division of GRB into two classes, long and short. The simplest interpretation is that they are all of similar origin, but have different values of one or more parameters, which are bimodally distributed. Most models of GRB permit a wide range of parameters. The observed anti-correlation of duration with spectral hardness is naturally obtained in fireball-debris-shock models (2–4) in which a higher Lorentz factor γ leads to a shorter GRB with a higher characteristic synchrotron frequency ν_c . Bimodality has been attributed (4) to the well-known bimodal distribution of interstellar density.

We re-examine this question. The most popular fireball models have been based on coalescing neutron stars (5). However, calculations (6,7) indicate that this process is nearly adiabatic and does not produce sufficient heating or neutrino emission to create an energetic fireball.

Accretion-induced collapse (AIC) of a bare degenerate dwarf has been calculated (8) to produce sufficient neutrino flux to power a fireball. AIC produces a ~ 10 s neutrino burst, as observed from SN1987A (the presence of a stellar envelope turns the neutrino energy into a supernova, while its absence permits a relativistic fireball). The duration of neutrino emission is a lower bound on the duration of the resulting GRB because the subsequent shock interaction, particle acceleration and radiation can stretch the observed GRB (as will the cosmological redshift), but cannot so readily shorten it.

AIC can explain only GRB with $T_{90} > 10$ s; shorter GRB require a different

TABLE 1. BATSE hardness and higher energy detections; nominal sensitivity ranges are indicated. Data are from 3B Catalogue.

	$T_{90} < 1$ s	$1 \text{ s} < T_{90} < 10$ s	$10 \text{ s} < T_{90}$
BATSE Hardness Ratio > 10	18	3	1
COMPTEL Detections (1–30 MeV)	2	2	20
OSSE Detections (0.06–10 MeV)	0	0	2
EGRET Detections (20–30,000 MeV)	0	0	6

process. Both classes of events occur at cosmological distances (1) and both probably involve neutrino fireball-debris-shock interactions, explaining their similar phenomenology, but the origin of the neutrinos must be different.

3B HARDNESS AND SPECTRAL DATA

If long and short GRB are produced by two distinct physical processes, members of these two classes may have different spectral properties and spatial distributions. This hypothesis can be tested with data in the 3B catalogue (9). We find that it is confirmed by qualitative differences in the spectral properties of long and short GRB and by quantitative differences in their spatial distributions.

The BATSE hardness ratio is a measure of the spectral slope in the range 50–300 KeV. Some of the entries in the 3B catalogue were also detected by COMPTEL, EGRET and OSSE, which indicate the presence of energetic photons above the BATSE band. The data are summarized in Table 1.

Photons of energies > 1 MeV are detected almost exclusively from long ($T_{90} > 10$ s) GRB. This is opposite to the behavior expected from an extrapolation of the hardness measured at lower photon energies by BATSE. Long and short GRB show fundamentally different spectral behavior, which cannot be explained by variation of a single parameter, such as ν_c . We conclude that they are intrinsically different objects, involving different physical processes, rather than different parameter ranges of a single class of event.

If long and short GRB have distinct physical origins they may have distinct spatial distributions, although this is not required. Table 2 presents the results of an analysis of C/C_{min} data in the 3B Catalogue (9). The whole Catalogue analysis shows that $\langle V/V_{max} \rangle$ for long and short GRB differ by 4.3σ . This confirms the hypothesis that long and short GRB have different spatial distributions and therefore different physical origins.

Subdivision of the data on the basis of integration times shows that this effect is produced by smoothly rising GRB, which do not trigger the detector when short integration times (64 ms) are used. We can predict that if these “smooth risers” could be separated from other long GRB they would have even smaller $\langle V/V_{max} \rangle$, and would be a pure AIC population, uncontaminated by GRB which have an intrinsically short time scale (and hence rapid rise) but

TABLE 2. $\langle V/V_{max} \rangle$ for short and long GRB. Data from 3B Catalogue.

	Whole Catalogue	64ms Data	256ms Data	1024ms Data
$T_{90} < 10$ s	0.385 ± 0.019	0.383 ± 0.021	0.373 ± 0.027	0.391 ± 0.022
$T_{90} > 10$ s	0.282 ± 0.014	0.370 ± 0.018	0.305 ± 0.017	0.276 ± 0.014
Difference	0.103 ± 0.024	0.013 ± 0.028	0.069 ± 0.032	0.114 ± 0.026

which are stretched to long T_{90} because they radiate slowly.

LONG GRB

Any model of long GRB must explain their > 1 MeV emission by a process distinct from that which produces their softer emission. Such a model was developed (10) for the extraordinarily intense 3B940217, which was also very long ($T_{90} = 150$ s) as measured by BATSE, and produced photons of energies as high as 18 GeV an hour after the initial burst (11), but had a BATSE hardness ratio of 3.83, roughly average. The energetic gamma-rays were attributed to π^0 decay or Compton scattering by energetic electrons and positrons (themselves produced by π^\pm decay) resulting from relativistic nuclei (fireball debris) entering a dense cloud of circumfireball matter. We now suggest that such a model is applicable to all long GRB, though the density and geometry of the cloud will necessarily vary from event to event, as will therefore the efficiency of production of energetic gamma-rays.

The cloud was attributed (10) to excretion by the progenitor of one of the neutron stars. That specific scenario can be replaced by one of AIC; when matter flows into an accretion disc surrounding the degenerate dwarf a fraction f of it is excreted from the disc and the binary. This is inevitable; matter accreting onto the dwarf must give up nearly all its angular momentum, which flows viscously outward in the accretion disc. Conservation of angular momentum gives $f = 1 - (r_{RCR}/r_{LSO})^{1/2}$ where r_{RCR} is the Roche circularization radius (12) and r_{LSO} is the radius of the last stable disc orbit (13), from which mass peels off the disc and is lost; $f \approx 0.5$, almost independent of the binary mass ratio.

A degenerate dwarf cannot accrete hydrogen-rich matter faster than $3 \times 10^{-7} M_\odot/\text{yr}$ because the Eddington limit applies to its thermonuclear luminosity. As a result, AIC is likely to be preceded by a period of accretion of at least 10^7 yr. The circumfireball cloud must be rather small ($< 10^{15}$ cm) (10) in order that it be dense enough for collisional interaction with the relativistic debris; for energetic collisional gamma-rays detected simultaneously with a 30 s GRB the time of flight suggests a size $\sim 10^{12}$ cm, but this may be an underestimate (by a factor up to γ^2) if the relativistic particles are moving radially outward at the time of collision.

Even the largest possible cloud is much too small to be freely expanding over an accretion time of 10^7 yr. It could be gravitationally bound in orbits outside

the binary orbit. Alternatively, accretion of helium or carbon-oxygen matter could proceed much faster because of the reduced thermonuclear energy release, efficient neutrino cooling (in burning of carbon and heavier elements) and the difficulty of igniting these fuels. Accretion of heavier elements resembles degenerate dwarf coalescence more than conventional mass transfer, and might be rapid enough (gravitational radiation-driven coalescence lasts ~ 30 yr) that escaping matter would still be close and dense when the final collapse occurred.

Apart from their gamma-ray emission, such events might resemble supernovae as energy deposited in the escaping matter is thermalized and radiated. The predicted gravitational wave emission of a long GRB, produced by AIC, is $\sim 10^{-9} M_{\odot} c^2$ (14,15), or even less if no matter is expelled.

SHORT GRB

Short GRB require a new mechanism. The requirement of producing 10^{51} erg of soft gamma-rays points to a catastrophic event involving one or more neutron stars; half the energy must be released in 10 ms in at least a few GRB. We suggest the collision of two neutron stars, probably occurring in a very dense cluster of stars. Such processes were suggested (16) as the origin of quasars. It is now considered likely that many galaxies possess massive black holes at their centers, which plausibly grew from dense clusters of stars. When the density becomes high collisions become frequent, and lower density stars are disrupted, leaving only neutron stars and black holes.

Colliding neutron stars have kinetic energy at impact ≈ 150 – 180 MeV/nucleon and speed (with respect to their center of mass) of ≈ 0.52 – $0.55c$. This is mildly supersonic, and the shock-heated matter with $k_B T \sim 100$ MeV is a copious source of neutrinos. Expelled matter cools by adiabatic expansion on the time scale $r/v \sim 0.1$ ms, permitting very short GRB. Matter retained by the neutron stars may radiate on the time scale of neutrino cooling, perhaps terminated by collapse to a black hole.

A cluster of radius R , containing N neutron stars each with mass M and radius r , has an evaporation time

$$t_{ev} \approx \frac{200N}{\ln N} t_{cr}, \quad (1)$$

where $t_{cr} \equiv (R^3/GMN)^{1/2}$ is the crossing time. The collision time is

$$t_{coll} \approx \frac{R}{r} t_{cr}, \quad (2)$$

where the cross-section, allowing for gravitational focusing, is $\approx rR/N$. The total collision rate is

$$\nu_{coll} \sim \left(\frac{GM r^2 N^3}{R^5} \right)^{1/2} \sim 10^{19} \frac{N^{3/2}}{R^{5/2}} \text{s}^{-1}. \quad (3)$$

A hypothetical cluster with $N = 10^8$ and $R = 10^{18}$ cm (virial velocity $\approx 2 \times 10^8$ cm/s) has a collision rate $\sim 10^{-14}$ s $^{-1}$ and a lifetime of $\sim 10^{19}$ s. About 10^9 such clusters would be required to produce the observed 10^{-5} short GRB s $^{-1}$ within $z \sim 1$; this number is comparable to the $\sim 10^9$ galaxies in that volume, and we cannot exclude that such clusters are commonly found at the centers of galaxies.

A much smaller number of more active clusters may be the sources of short GRB, in which case repetitions may be found. The present upper bound (17) on the repetition rate of GRB is not stringent.

A simple estimate shows that the gravitational radiation emitted in the collision of two neutron stars is $\sim 10^{-2}GM^2/r \sim 10^{51}$ erg into a broad band around ~ 3 KHz. The wave-train would be very different from that of coalescing neutron stars.

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